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FABRICATION AND EVALUATION OF A
CRYOSTABLE Nb$_3$Sn SUPERCONDUCTOR
FOR THE MIRROR FUSION TEST FACILITY (MFTF-B)

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Summary

The MFTF-B magnet system requires two 12.5T, 36 cm bore, insert coils. These coils are being constructed with a cryostable Nb$_3$Sn conductor manufactured by Furukawa Electric Co. The conductor consists of a core soldered into a cold-worked copper housing, which provides strength. The Nb$_3$Sn core is made by a triple extrusion bronze process. A total of 57 lengths, each 295 m long, have been made and tested. We have made extensive tests on this conductor; these tests include critical current, ambient and 4.2 K mechanical property measurements, critical current as a function of tensile strain, and bending tolerance tests. The critical current density was found to be quite anisotropic in this conductor, with $J_c(12T) = 650A/mm^2$ for field perpendicular to the conductor wide face, and $J_c(12T) = 500A/mm^2$ for field parallel to the conductor wide face. These values of current density are among the highest reported for a production lot of Nb$_3$Sn conductor.

Introduction

This paper will describe the fabrication and evaluation of prototype and production lengths of a cryostable Nb$_3$Sn superconductor for use in the Mirror Fusion Test Facility. The design of these coils (referred to as axicell coils) and the conductor have been discussed previously.[1] The coils produce a central field (with background) of 12.0 T in a clear bore of 36 cm. Two coils are required for MFTF-B; each coil consists of 27 double pancakes and hence a total of 54 double pancake lengths, each 295 m long, are required. The operating current is 1500 A, and the maximum field at the conductor is 12.52 T.

The initial design for MFTF-B employed a different coil configuration which utilized all NbTi conductor. Subsequent analysis showed that improved operation could be achieved with the high field axicell design. However, the implementation of this major change, without appreciable delay in the project completion date, meant that the Nb_3Sn conductor procurement must be rapid and that the vendor must deliver conductor on a tight schedule (first conductor delivery 12 months after receipt of the order).

Conductor Manufacture

Furukawa Electric Co., Ltd. was awarded a fixed-price contract to manufacture this conductor. A major technical factor in the choice of Furukawa was their experience in fabricating conductor for the Cluster Background Coils (CBC) at JAERI.[2] The CBC and MFTF-B conductors are similar in that they both consist of a reacted Nb_3Sn core soldered into a cold-worked copper housing. Also, both the CBC and the MFTF-B cores are fabricated using the Furukawa version of the bronze process. A major difference between the two conductors is that the CBC conductor was designed for 10 T operation, whereas the MFTF-B coil operates at 12.5 T. Several problems, including degradation of the I_c due to strain and anisotropy in I_c, are more severe in the higher field MFTF-B application. In addition, the Lorentz forces acting upon the conductor are considerably higher. These effects will be discussed in the section on Test Results.

Fabrication was initiated on a pre-prototype length in order to gain manufacturing experience while the new materials (Nb and bronze) were being assembled. The Nb used in this pre-prototype length was not of high quality, and it produced filaments which were non-uniform in cross-section. This problem has occurred in other Nb_3Sn composites.[3] several important observations were made on this pre-prototype which were incorporated into the prototype design: a) The anisotropy in critical current (see Test Results section for an explanation) was somewhat higher than anticipated, and to compensate for this the Nb_3Sn volume fraction was increased; b) during billet extrusion, some nonuniform deformation occurred near the diffusion barrier requiring an improvement in the third stage billet stacking; c) some Nb_3Sn formation was observed to occur during the bronze annealing, so the annealing temperature was adjusted. The fabrication steps for the prototype length and the 56 production lengths will now be discussed.

In order to avoid production problems previously reported for bronze process conductors[3,4] the Nb, Cu, and bronze raw materials were carefully specified and prepared. The Nb rods, obtained from Teledyne Wah Chang Albany (TWCA) were specified with respect to chemistry, grain size, hardness, surface condition, and freedom from porosity. The bronze composition is 14.3 $\pm$0.5 wt % Sn, 0.23 $\pm$.05 wt % Ti, balance Cu; the bronze to Nb ratio is maintained between 2.6:1 and 3.2:1. The copper has an initial RRR greater than 200 and a purity greater than 99.99%.

The multifilamentary composite is fabricated in three extrusion steps, with intermediate cold drawing steps. The first extrusion consists of a Nb rod in a bronze pipe; after extrusion and drawing, lengths of this material are loaded into a second billet (380 Nb cores), extruded and drawn. The final extrusion billet consists of approximately 380 second extrusion cores inside a Nb diffusion barrier and a copper can. This extrusion is drawn and then aspected to produce the superconductor core 2.11 mm by 6.91 mm in cross-section. Reaction of these lengths to form the Nb_3Sn is performed at 700° C for several days in an inert atmosphere. Three lengths 300 m each are heat-treated simultaneously on a set of nested mandrels 600, 700, and 800 mm in diameter. The mandrels are stainless steel with spiral machined grooves to prevent the turns from touching and bonding during heat treatment. The diameters of the mandrels are chosen to minimize the amount of strain the Nb_3Sn filaments will experience during subsequent processing and coil winding.[1]

Throughout the processing, quality control is maintained by checks on (a) cracks or other flaws in the bronze, (b) dimensions, (c) bronze:Nb ratio, (d) uniformity of composite cross-section. In addition, eddy current detection is performed on the composite during processing to find inclusions and to monitor the copper to non-copper ratio.

Finally, the superconductor core is clad with cold-worked Cu for additional strength and to provide cryostability. The cladding consists of a channel piece and a "hat" which are soldered onto the core (Fig. 1) with 60 Sn, 40 Pb solder. The outside surfaces of the Cu cladding are coated with copper oxide so that the solder does not wet these surfaces. The quality of solder bond is monitored ultrasonically, and no completely unbonded zone on both wide faces greater than 0.5 cm is permitted. In addition, no more than 20% of total bondable area in any 10 cm length may be unbonded.

The soldering line is designed so that the strain on the reacted Nb_3Sn core is minimized. This is accomplished by a straight-through line design, a moving core payoff, and large diameter rolls and guides. The copper cladding is protected from annealing by careful control of solder bath temperature and a fast-drain system, which can be activated in the event of a power failure. Only three lengths out of a total of 60 lengths produced were out of specification with respect to solder bond quality. The dimensional specification on the completed conductor is 5.21± .1 mm by 11.00± .1 mm; actual extrema are 5.226 mm to 5.163 mm on the thickness and 11.00 mm to 11.06 mm on the width. The fabrication of the required 57 lengths (54 needed, plus two spare lengths and the prototype length) were completed on schedule with no major problems. Early in the production period, some bronze pipes were found to have cracks, but they were replaced without a serious delay in production. The processing of raw material for production lengths began in August 1983, and the final length was ready for shipment by June 15, 1984.

Test Results

The coil design requires this conductor to withstand substantial straining during construction and operation; hence a comprehensive series of tests were performed on the prototype length in order to assess the affect of strain on critical currents. These tests were designed to provide engineering data for this particular coil; however, the empirical scaling relationships developed by Ekin[5] can be used to interpret the results.

The first test was designed to evaluate the strain sensitivity of the Nb_3Sn superconductor insert, since this insert is processed through the cladding line after reaction to form Nb_3Sn. The insert was reacted in four configurations (straight, R = 40 cm, 20 cm and 10 cm). The curved reacted specimens were straightened and all specimens tested. The results, as shown in Figure 2 indicated an enhancement in current carrying capability at the operating strain condition (approximately .002 bending strain). The bending strain induced into the specimens (from straightening) did not show any I_c degradation (from the straight specimens) up to .0048 bending strain. The relatively small I_c enhancement due to bending strain can be attributed to a minor neutral axis shift effect.[5]

Another test involved the evaluation of the tolerance due to bending of the completed conductor, including the copper cladding. Conductors with inserts reacted on a 70 cm diameter were bent both in the "right direction" (decreasing reaction diameter) and in the "wrong direction" (opposite direction from the reacted shape), thus producing a bending strain in the insert. The measurements again showed (Fig. 3) an increase in I_c up to a bending strain condition of approximately 0.008 (for both the right and wrong way bending) which has been defined as ε_{IRREV}. The ε_{IRREV} = 0.008 was used to develop minimum radius conditions for a right/wrong way bending tolerance that could be used during fabrication of the magnet.

The I_c vs. bending results in both the insert and conductor illustrated an increase in current carrying capability before degradation begins (Figures 2 and 3). This increase in I_c vs. bending strain has been attributed to a neutral axis shift in the conductor. Since the neutral axis shift has the potential of increasing the strain in the conductor, an analytical technique was developed to estimate this strain .

Typical Nb_3Sn conductor current carrying characteristics are shown schematically with respect to intrinsic strain (Nb_3Sn fiber uniaxial strain) in Fig. 4 as shown. The curve can be represented by an empirically-developed equation. The constants used to represent the typical Nb_3Sn characteristics[5] are taken as B = 12.5T and T =4.2K. The effect of bending strain on the critical current can be estimated by integrating within the limits of the applied bending strain.

The state of prestrain (ε_i) in the matrix is important in considering the bending strain effects because it influences the position of the neutral axis during bending. To obtain the critical current of the bent conductor $J_c(\varepsilon)$ is integrated over the different tensile and compressive regions of the conductor (averaging over the uniaxial strain curve). The changes in J_c without a shift in the neutral axis are nearly symmetrical about point A (Figure 4) and the net changes in J_c will be slight.

A large prestress shifts the neutral axis from the center of the conductor toward the center of curvature during bending. Under this condition, the changes in J_c (about point A) will no longer be symmetrical. A larger portion of the superconductor will experience an applied tensile strain and the net J_c value will, therefore, increase initially during bending. By knowing the amount of J_c increase and the initial prestress of the matrix (both developed from tests), an estimate of the additional strain (over the simple bending relationship, $\varepsilon = d/D$) due to the neutral axis shift can be developed. The conclusion from this analysis is that a neutral axis shift does occur, but the effect is small, leading to an additional strain of .05% compared with the maximum strain of 0.2% calculated for handling this conductor.

A similar Nb_3Sn conductor clad with cold-worked Cu had shown a significant reduction in I_c due to cladding[6]. This effect was evaluated for the present conductor and found to be only 6-10%.

A number of routine measurements were made on the production lengths in order to evaluate reproducibility. Each final extrusion produced three lengths at final size, so a sampling plan was devised so that samples were taken from each end of these three lengths but duplicates were eliminated. Samples were taken after cladding and critical current measurements were made on straight samples in a 13 T split solenoid with a field uniformity of $\pm 1\%$ over a 5 cm length. Critical current measurements on a large cross section monolith such as this are difficult due to the long current transfer distance[7] arising from current transfer across the resistive bronze matrix. The spacing between voltage taps was reduced to 1 cm in order to reduce the contribution of this current transfer voltage, and then this contribution was removed by constructing a new base line. A criterion of $P = 10^{-11}$ Ω-cm was then used to define the critical current. Several samples of prototype material were measured first with the field perpendicular to the conductor wide face and then parallel to the wide face. These measurements showed a rather large degree of anisotropy, with the I_c (perpendicular) being about 25% higher than I_c (parallel). This effect has been observed in other highly aspected conductors[8] and experiments are in progress to understand this effect.[9] In the MFTF-B coil design the field is parallel to the wide face, so that I_c (parallel) is the applicable value and I_c (parallel) was measured for all production lengths.

Critical current measurements were made in a total of 80 samples from the production lengths. The average value is I_c = 5200 A at 12.0 T and I_c = 4600 A at 12.5 T and all values are within 11% of the average. All samples greatly exceeded the specification value of 3400 A at 12.5 T. The average critical current value I_c = 5200 A corresponds to a critical current density in the non-copper area J_c (12 T) = 520 A/mm^2. These values are among the highest yet reported for a production order of this size.

Conclusions:

1. The bronze process with a Ti-doped, high-Sn-content has been used successfully to fabricate a large quantity (17,000 m) of cryostable Nb_3Sn superconductor.
2. The results of bend tests and other mechanical property tests indicate that this reacted Nb_3Sn conductor is capable of withstanding the handling and Lorentz forces anticipated in the MFTF-B axicell coils.

The authors would like to acknowledge the contributions of their colleagues at LLNL*, General Dynamics/Convair, and Furukawa Electric who have contributed to this project. Steve Mance and Rick Gross of LLNL performed the important yet tedious task of measuring the critical currents of approximately 100 samples. As MFTF Magnet Program Leader, Ted Kozman has provided continuous encouragement and support.

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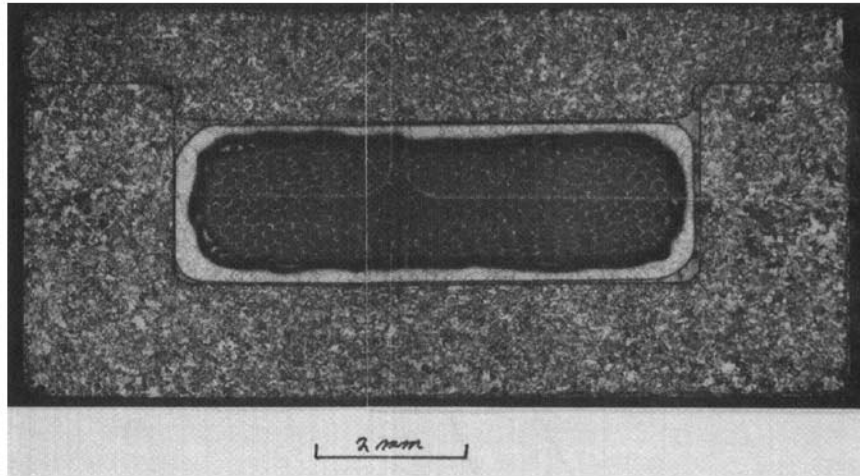9. M. Suenaga, Paper NMI, these proceedings

Fig. 1a Cross-section of the conductor showing the cold-worked Cu cladding (U-shaped channel and "hat") with insert soldered in place.
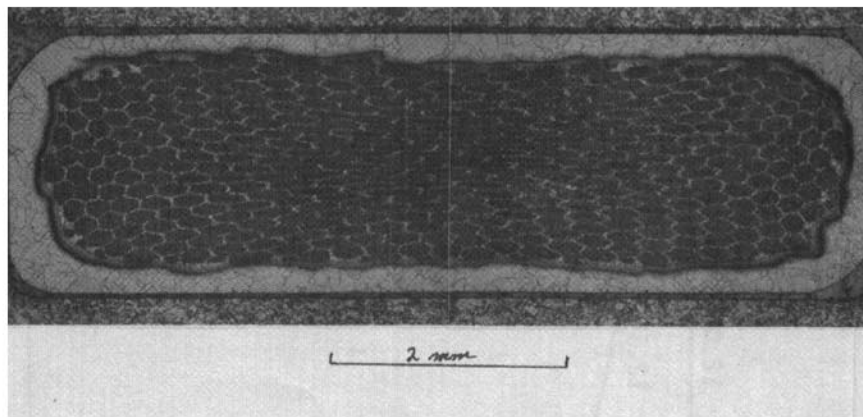

Fig. 1b Enlarged section of the insert showing outer copper, Nb diffusion barrier and Nb_3Sn in bronze matrix.

THIS STRAIN CONDITION BEST
SIMULATED THE NET BENDING
STRAIN STATE OF THE 1st TURN

6000

12.0T

5000

12.5T

CRITICAL CURRENT, I_c

4000

3000

2000

REACTED ON A R = 40cm

REACTED ON A R = 20cm

REACTED ON A R = 10cm

0   .001   .002   .003   .004   .005   .006   .007   .008   .009
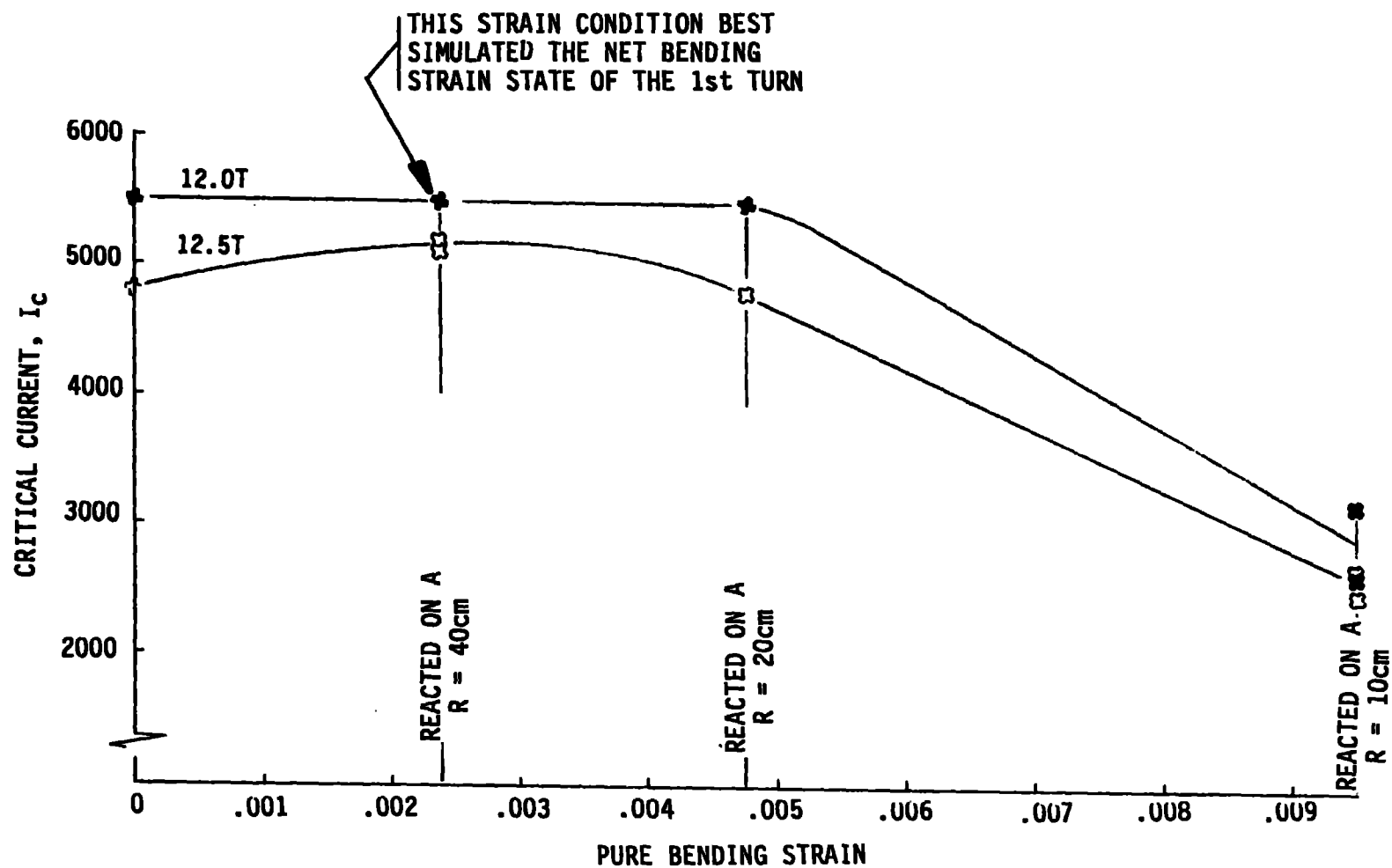
PURE BENDING STRAIN

Fig. 2   Effect of bending strain on critical current
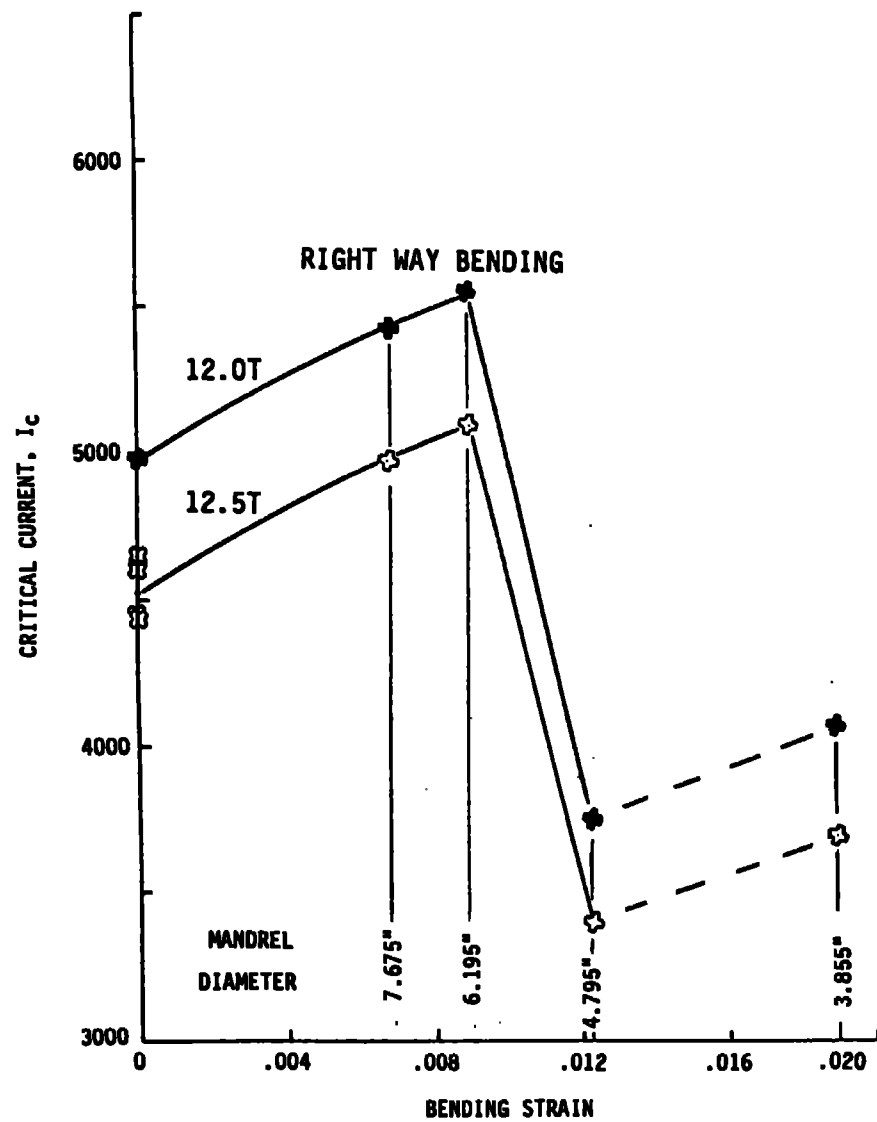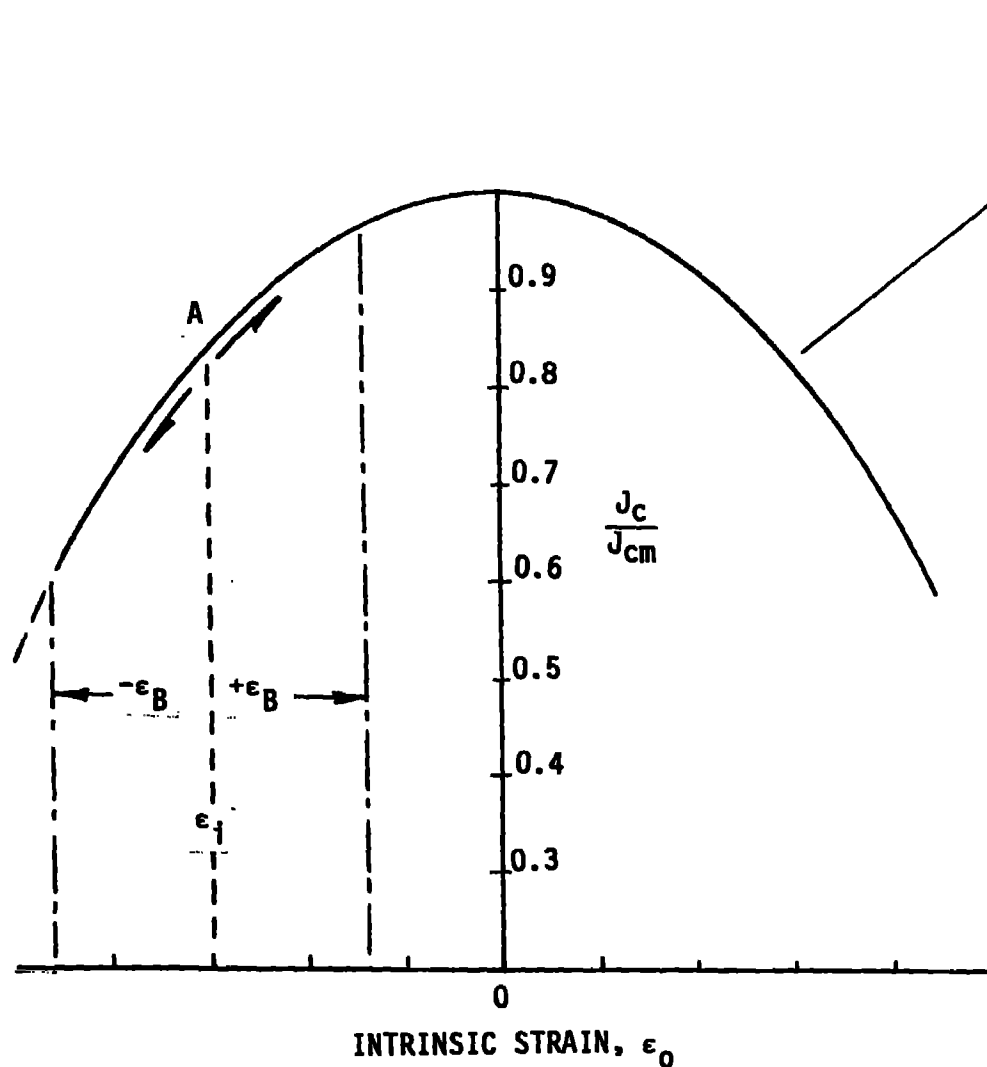for samples of the conductor insert.
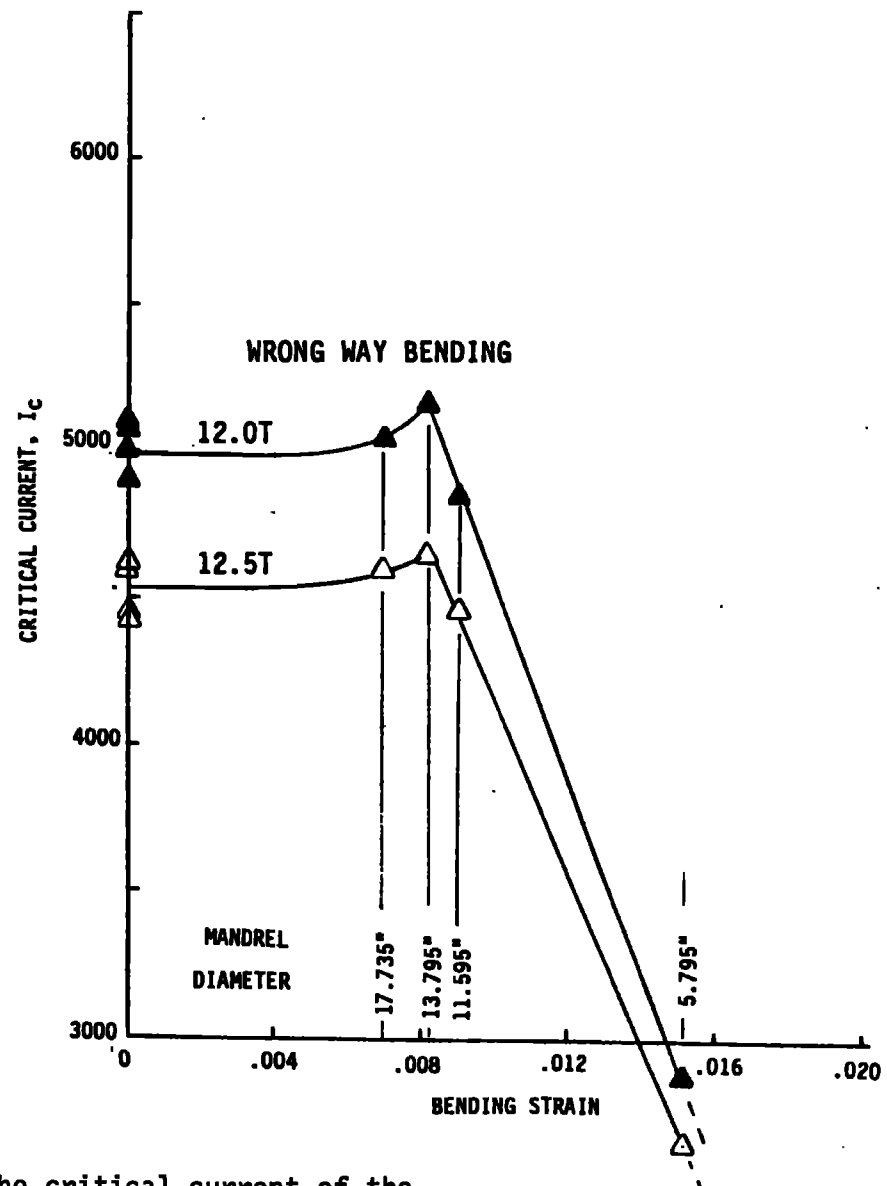
Fig. 3 Effect of bending strain on the critical current of the
current of the assembled conductor (insert and Cu cladding).

$$\frac{J_c(\varepsilon_1 + x)}{J_{cm}} = \left[\frac{B^*_{c2}(\varepsilon_1 + x)}{B^*_{c2m}}\right]^{n-p} \left[\frac{1 - \frac{B}{B^*_{c2}(\varepsilon_1 + x)}}{1 - \frac{B}{B^*_{c2m}}}\right]^g$$

WHERE:

$$\frac{B^*_{c2}(\varepsilon_1 + x)}{B^*_{c2m}} = (1 - a|\varepsilon + x|^u)$$

USING:

a = 900 $(\varepsilon_0 < 0)$

B = 12.5T

B^*_{c2m} = 21T (upper critical field)

n = 1, P = 0.5, g = 2.0, u = 1.7 (for Nb₃Sn @ 4.2K)

THE EFFECT OF BENDING STRAIN ON THE CRITICAL CURRENT
CAN BE ESTIMATED USING:

$$\frac{I_c}{I_{cm}} = \frac{1}{2\varepsilon_B} \int_{-\varepsilon_B}^{\varepsilon_B} \frac{J_c(\varepsilon_1 + x)}{J_{cm}} \, dx$$

Fig. 4 Schematic diagram illustrating the effects
of bending strain on the critical current.